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An engineering critique of Great Zimbabwe

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The dry-stone structures at Great Zimbabwe National Monument represent one of the most impressive accomplishments of pre-colonial engineering in sub-Saharan Africa. This paper presents a general discussion and assessment of the building techniques employed in construction of these walls.

Great Zimbabwe National Monument comprises a number of dry-stone walled enclosures (Fig. 1), constructed by an eleventh to sixteenth century African community, who resided in daga (adobe) huts. Although the site is not the earliest occurrence of dry-stone walling in Zimbabwe (Garlake, 1973) it

represents the most impressive example of a construction technique that has been practised in Southern Africa over the last thousand years. The construction of such a large complex of dry-stone walls, some standing 10 m high, not only demonstrated an intuitive understanding of basic

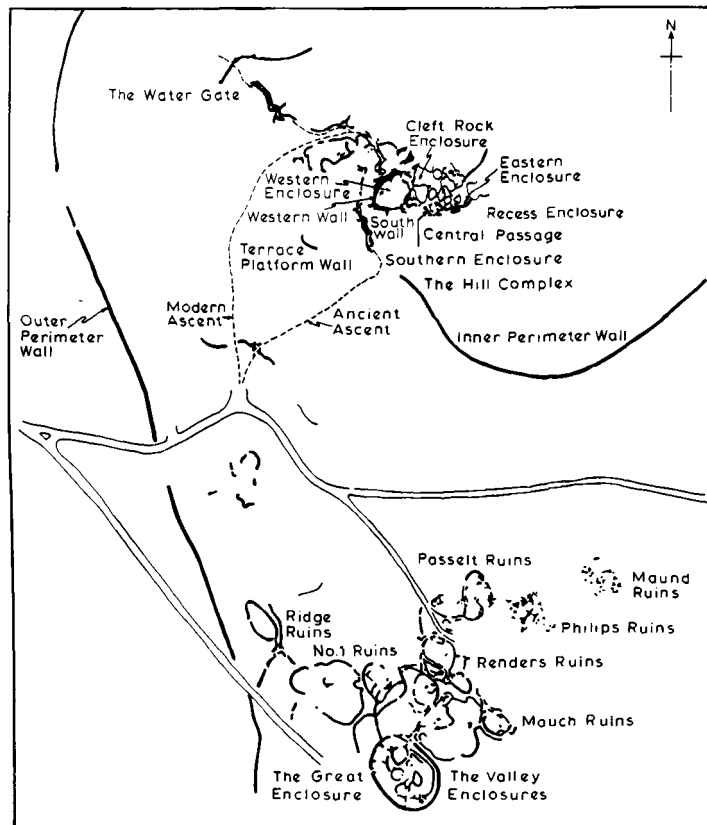


Fig. 1: General layout of Great Zimbabwe

engineering principles, but seemingly required a considerable infrastructure and organization capable of quarrying, transporting and laying the granite blocks.

There are distinctive variations in the appearance of the dry-stone walls at Great Zimbabwe and these have been recorded and discussed in a number of previous studies (Hall and Neal, 1904; Schofield, 1926; Stevens, 1931; Van Riet Lowe, 1945; Whitty, 1961; Summers, 1971; Garlake, 1973). The contrasts in wall architecture are most apparent at the Great Enclosure (Plate 1). Walls with regular, horizontally coursed blocks stand alongside those built with irregular, poorly coursed blocks. The contrasting differences in the appearance of the walls have been taken as being indicative of technological and cultural developments during occupation of the site (Whitty, 1961; Garlake, 1973).

In the past studies it has often been the architecture of the dry-stone walling that formed the basis for the many varied theories as to the origins and development of Great Zimbabwe. Early studies generally ascribed to the view of ancient origins, suggesting that the regularly coursed walls were the earliest, built by European or Arab

civilization, and that the poorly coursed walls were merely decadent reproductions by later African occupants of the site (Hall and Neal, 1904). However, a number of archaeological and architectural studies have discredited such racially prejudiced theories and conclusively shown that Great Zimbabwe was built by an African civilization (Garlake, 1973). A few of the more important studies are briefly reviewed below.

Schofield (1926) suggested that it was possible to establish the chronological development of Great Zimbabwe by studying the construction sequences of the walls. Schofield's study was the first to identify construction sequences, recognizing that adjoining walls were never bonded together, hence the later wall must be leaning against the earlier. The study also noted that many of the walls had been built in a number of stages. Schofield used the term 'composite construction' to describe the development of these walls. In its conclusion, the study suggested that the poorly coursed walls were the earliest and that the differences were due to levels of care and skill and variations in the materials used.

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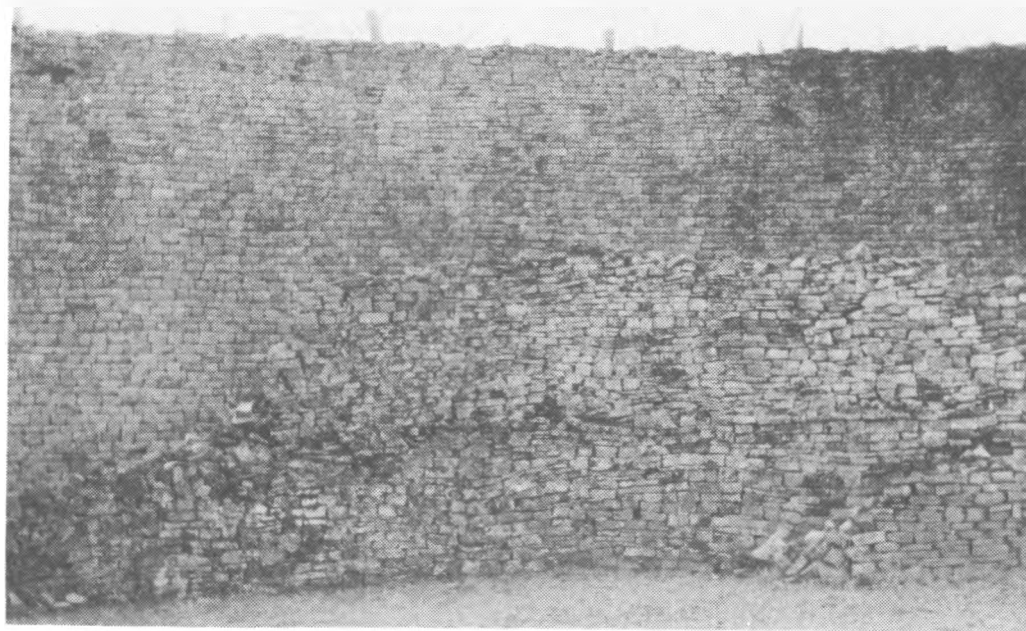
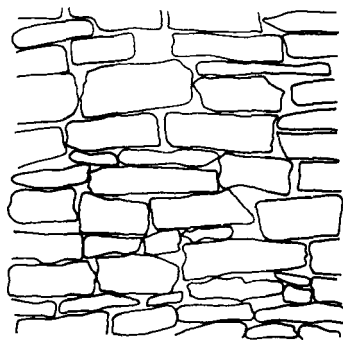
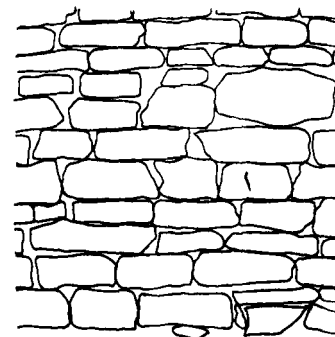


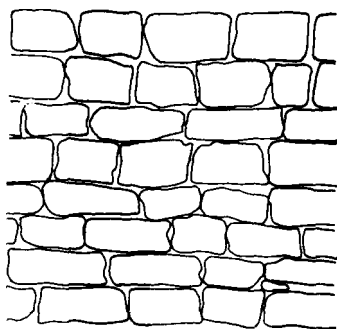
Plate 1: Free-standing walls, Great Enclosure



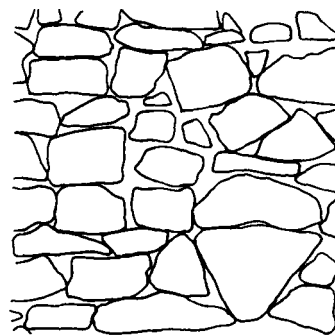
Class P



Class PQ



Class Q



Class R

Fig. 2: Wall styles

Enclosures at Great Zimbabwe Caton-Thompson (1931) recognized the importance of the relationship between the layout of the dry-stone walls and daga huts. Her work showed that free-standing walls were often built between and leaning against the daga huts.

Whitty (1961) published what has become the definitive study of wall styles at Great Zimbabwe. The work proposed a system for classifying wall styles based on objective observations of the face blocks, quality of workmanship and other features associated with each type of wall. The classification divided the walls at Great Zimbabwe into four main categories (Fig. 2):

Class P characterized by uneven course varied sized blocks and wavy surfaces between adjacent courses;

Class Q characterized by equal sized blocks which form a very regular

pattern with the blocks coursed in horizontal layers;

Class PQ intermediate between class P and Q;

Class R characterized by irregular blocks piled in a chaotic style with no evident courses.

By classifying each wall within the Great Enclosure and studying construction sequences, Whitty was able to establish the following chronological relationship between wall styles: class P earlier than class PQ earlier than class Q earlier than class R.

Generally, previous studies comparing the architecture of the walls have concluded that the improvements in coursing and overall appearance were due to developments in building technology. This paper assesses and compares the building methods employed in the construction of the dry-stone walls.

Quarrying

The blocks used for wall construction were mostly obtained from quarrying the exfoliating slabs of granite which surround the site. However, in both the early class P and class R walls at Great Zimbabwe naturally fractured blocks have been incorporated into the construction; these blocks are often highly weathered, unlike the quarried blocks which only exhibit weathering along the exfoliation surfaces.

A number of alternative methods employed to quarry the blocks have been proposed. Hall and Neal (1904) suggested that blocks were obtained by percussive splitting of the bedrock. Schofield (1926) and Summers (1971) have proposed that blocks were obtained by fire-setting. In addition, Summers suggested that the quality of the blocks produced could be carefully controlled by quenching the heated granite with water.

Recent experiments at Great Zimbabwe (Dube, 1991) have shown that the granite was most likely quarried by a combination of both fire-setting and percussion. A wood fire made along the face of the exfoliation step causes the bedrock to split into sections between 1 and 2 m square, from which the building blocks are then obtained by percussion. Generally the granite splits naturally into parallel sided blocks, which require little or no dressing before incorporation into the walls. The experiments also confirmed that quenching of the rock with water is unnecessary.

It is well known that rock is poor conductor of heat and so an increase in the temperature at one face will induce a thermal gradient. The minerals that comprise the granite have different specific heats and coefficients of thermal expansion causing them to expand at different rates. On heating the minerals expand by different amounts, exaggerated by the effects of the thermal gradient, and so tensile stresses develop between the grains causing fracture of the granite.

The quarrying process has had a detrimental effect on the mechanical properties of the blocks produced. In

addition to the main fracture, fire-setting and percussion have often caused micro-cracking of the blocks. These micro-cracks ensure that the blocks have a low flexural tensile strength, frequently leading to failure once incorporated into the wall. Disturbance of the wall structure due to block fracture has been a contributory factor in the failure of a number of walls; excessive cracking of the face blocks is commonly observed in unstable walling.

Recent work at Great Zimbabwe has established a distinctive correlation between wall styles and face block geometry (Walker, 1993). On average the blocks in class P, PQ and Q walls measure approximately 220 mm long and 180 mm wide. Blocks were most often laid with the exfoliation surfaces horizontal, and so block height was determined by the thickness of the exfoliation slab at the quarry site. The block heights gradually increased with development of the wall styles, from an average between 60 and 90 mm in class P walls to between 90 and 140 mm in class Q. Typically the thickness of exfoliation steps in granite increase with depth below surface level (Twidale, 1982). Therefore it would seem that the sequence of wall styles was an indirect result of continued quarrying of the blocks, rather than due to any direct development of the construction techniques.

Wall Construction

Function

The dry-stone structures at Great Zimbabwe perform two functions; as terracing or retaining walls in order to increase an area for occupation, or as free-standing walls which act as partition walling to form a series of enclosures. The earliest walls (class P) were predominantly retaining structures and the later walls (class PQ and Q) were mostly free-standing. This change of function is commensurate with the development of the site away from the Hill Complex and into the valley. The walls were not built for defensive purposes, as can easily be discerned from inspection of the site.

One of the main function of the free-

standing walls in the valley was to form enclosures around a complex of huts. Many of these walls were clearly not intended to be 'permanent' since their stability depended on the more temporary hut structures. Walls were often built onto the remains of previous huts and the foundations of earlier dry-stone structures, indicating that the site was continually developing. An advantage of dry-stone construction is the ease with which walls may be dismantled and reconstructed to suit requirements, which undoubtedly contributed to its widespread success at Great Zimbabwe.

Excavations of the backfill deposits behind retaining walls show a stratigraphy of hut construction representing continued occupation over a number of years (Garlake, 1973). As the backfill deposit increased, retaining walls were often increased in size to suit requirements. Retaining walls were also built in one complete operation to their full height. Although the form of construction of the retaining walls differs little from that of the free-standing walls, they were clearly required to perform a more permanent function.

Form of construction

The form of construction adopted for both the free-standing and retaining walls did not vary during the development of Great Zimbabwe.

Free-standing walls were formed by the construction of two outer faces of carefully stacked blocks infilled with core material. The core material comprised granite blocks less regular in both size and shape but laid in 'courses' similar to the face (Plate 2). Occasionally daga pieces from hut remains and fragments of other rocks, such as ironstone, were also incorporated into the core.

Although dry-stone walls are a widespread form of construction found in many countries, the construction of free-standing walls up to 10 m high makes those at Great Zimbabwe unique. The form of construction adopted in Zimbabwe differs from that found elsewhere. Generally through- or tie-stones are used to directly



Plate 2: Cross-section of free-standing walls

connect the two outer faces of the wall, however, they were never used at Great Zimbabwe. Through-stones significantly enhance the horizontal integrity of the structure, by inhibiting wall failure due to separation of the faces. The lack of through-stones at Great Zimbabwe can be attributed to the lack of suitable blocks for the relatively thick wall construction undertaken. The lack of suitable stones is exhibited by the use of timber or schist for the doorway lintels, rather than granite. The structure of the walls has been weakened by the lack of a horizontal connection, as demonstrated by the present structural instability at the site (Walker and Dickens, 1991).

Retaining walls were built using two different forms of construction. Some were built with two outer faces and core material stacked between, in a similar manner to free-standing walls. These structures act primarily as mass gravity retaining walls relying on their mass to resist the overturning effects of

earth pressures. Retaining walls were also built incorporating only one outer face with core material stacked into the backfill. Since the main structure of this type of walls is insufficient to withstand full lateral earth pressures, as in a mass gravity wall, the core acts to stabilize the soil. Both forms of retaining wall construction are found in class P, PQ and Q walling.

The stability of dry-stone wall structures depends largely on limiting geometrical considerations and on the internal structure of the walls. The most important geometrical parameters are batter (inward slope of the wall face) and the ratio between height and base width (slenderness ratio). It is likely that the development of Great Zimbabwe was accompanied by a trial and error approach to construction, and so the geometrical limitations necessary for stability would probably have been learnt from experience.

Battering of the wall face reduces the quantity of material required for construction, but more importantly enhance the stability of the wall by lowering the position of its centre of gravity. An optimum value for the batter of dry-stone walling is considered to be 1:6 (Brooks, 1986). The values for batter measured for a number of walls at Great Zimbabwe varied as follows: class P 1:6–1:29, class PQ 1:6–1:19 and class Q 1:9–1:34. Although the values vary considerably throughout, the necessity to provide a batter was clearly apparent from initial construction and exhibited little change during subsequent development. The batter provided was often steeper than that considered most suitable, but this may have arisen from the exceptionally regular nature of the blocks compared to most other forms of dry-stone walling.

The slenderness ratios for a number of walls varied as follows: class P 1,25–1,73; class PQ 1,34–2,81 and class Q 1,49–2,56. An upper limiting value of slenderness ratio considered sufficient to ensure the stability of dry-stone retaining walls is 3,33 (Jones, 1990). Although all of the walls measured had slenderness ratios less than this value, it is apparent that the during development of

Great Zimbabwe the slenderness ratios of the walls increase. This increase probably reflects the experience gained through continued construction.

Series of unbroken vertical joints for ten courses and more are common in all wall styles. It would seem that the construction of walls with consistently broken vertical joints was not of concern to the builders. In later class Q walls face blocks were dressed *in situ* (Garlake, 1973). However, the consistently poor bonding indicates that this was undertaken for mainly aesthetic reasons rather than to improve the structure of the walls. Flush vertical joints significantly weaken the integrity of the walls, as the wall faces are more prone to bulging and toppling.

Observation of the core material in partially collapsed sections indicate that it was carefully laid and not random rubble as has been proposed (Hall and Neal, 1904; Van Riet Lowe, 1945; Plate 2). Further, the wall faces are insufficient to contain the lateral pressures that a random rubble core would exert. As the irregular core blocks are of a similar size, and not graded, there tends to be a relatively high proportion of voids in the internal structure of the walls. This also impairs the integrity of the walls by increasing the potential for relative displacements within the core material, arising from any disturbance to the structure such as ground settlement or vegetation growth.

Method of construction

Quarrying was the most labour intensive activity in the construction of the walls. It involved the collection of firewood, fire-setting, percussive splitting and transportation of the blocks to the site. Generally the quarries were situated within a radius of 1 km of the main site. In the absence of accurate measurements, a conservative estimate of the total quantity of granite used in the construction of Great Zimbabwe is between 50 000 and 75 000 tonnes, based on measurements of the outer perimeter wall of the Great Enclosure. On average blocks weigh approximately 10 kg, giving a total of between 5 and 7,5 million blocks quarried and transported to the site.

A skilled dry-stone mason is capable of constructing approximately 2 to 4 cubic metres of walling per day (Brooks, 1986), depending on the type of stone used. On this basis a team of 100 masons and 1 000 labourers would have been capable of building the Great Zimbabwe in one year. Although this was clearly not the case, the above figures do indicate that wall construction would not have been a major drain on human resources for a population estimated to be between 10 000 and 20 000.

The walls were most likely built in progressive stages, first laying a course of outer face blocks to obtain the line of the wall, which was then infilled with core material. The relatively uneven proportions of many walls suggest that construction was carried out by eye, rather than using string lines or other similar building aids. However, the uniform batter of the outer wall of the Great Enclosure suggests that some form of aid to building was used in this case.

Retaining walls were probably built without the need for scaffolding or other temporary structures, by working from the backfill. However, the construction of free-standing walls above 2 m high would have required some form of temporary access. Garlake (1973) has suggested that walls were built as a progressive step, and access was obtained by climbing the partially completed wall face. But the inspection of partially collapsed sections of walling indicates that access in this manner was unlikely, as it would have caused considerable disturbance. Although many walls were probably built with a continuous steeped face, access for construction was almost certainly obtained using temporary structures such as timber scaffolding or earth or stone ramps.

Foundations

Differences in the wall foundations have been taken as marking an improvement in construction techniques (Whitty, 1961; Garlake, 1973). However, from inspection of existing walls, it is apparent that the main factor which governed the change in foundation construction was geological variations of the terrain. The earliest walls

were predominantly built on the bedrock outcrops of the Hill Complex. The construction of walls directly onto granite outcrops is a natural preference, since the bedrock provides a rigid base, avoiding the problem of ground settlement. Where gaps were present between the outcrops they were filled with a combination of soil, debris and blocks; otherwise no special measures were carried out in the preparation of the foundations for these walls. The natural topography of the site meant that walls were often built onto outcrops with an excessive inclination. To prevent the likelihood of the wall simply sliding down the rock face the builders used a daga-based mortar to bond the blocks onto the bedrock, and thereby strengthen the foundation. The success of this type of foundation is reflected by the continued construction of walls in the valley onto inclined outcrops, even where site topography is much less restrictive.

As the site expanded, walls were built directly onto residual soil deposits. In many cases the top layers of soil were removed to ensure that the wall was based onto firmer ground. The trenching of the foundations ended with the construction the outer wall of the Great Enclosure, where excavations were taken up to 1 m below ground level (Summers, 1961).

The foundations of this wall were also corbelled in an attempt to spread the weight of the structure, but the amount of corbelling provided, only 200 mm in a wall over 5 m wide, will not have had any significant beneficial effect. It is, however, indicative of a realization of the need to provide adequate foundations. The benefit of the trenching undertaken for the outer wall of the Great Enclosure is demonstrated by its present condition, compared to other similar walls which have partly or wholly collapsed.

Structural assessment of retaining walls.

In order to assess the integrity of retaining walls built at Great Zimbabwe a simplified stability analysis was undertaken. Mass gravity earth retaining walls rely upon their self weight for stability, and are considered adequate by satisfying the following criteria

(Arya and Gupta, 1983):

- i) There should be no overturning of the wall as a whole or any part. The minimum factor of safety against overturning should not be less than 2,0;
- ii) The pressure at the toe (front base) of the wall should remain less than the safe bearing capacity of the soil or rock strata. The factor of safety with respect to ultimate bearing capacity should not be less than 3,0;
- iii) The sliding or shearing stress should remain less than the safe value of the shear or sliding resistance. A minimum factor of safety of 1,75 should be applied.

The structural assessment was undertaken on the basis of recorded wall dimensions and analysis of soil samples taken from Great Zimbabwe. The factors of safety for all three conditions were generally above the limiting conditions; the factors of safety were, for overturning between 2,3 and 9,0, bearing capacity between 2,5 and 4,3 and sliding between 1,8 and 18. Typically the factors of safety decreased in the later walling, which exhibits an improved understanding of dry-stone construction. Any wall that did not satisfy these limiting conditions may have failed. Bearing capacity checks carried out for a number of free-standing walls built onto residual soil confirmed that the foundations provided were adequate. A site investigation of the ground conditions at the Great Enclosure confirmed the necessity for trenching the foundations 1 m below surface level, due to the presence of weaker soil strata above (Walker and Dickens, 1991).

Although overall geometrical limitations must be satisfied to ensure stability, the form of construction has meant that the walls have a very low internal factor of safety. Construction with numerous vertical joints, high voids ratio in the core and the lack of through-stones have meant that ground settlements, for example, have often induced wall failure.

Structural instability at Great Zimbabwe is not a recent phenomenon. Walling in the Great Enclosure required repair during the main occupation of the site. A number of retaining walls have additional buttresses

built along their base, added in order to prevent failure. However, despite some of the inherent weaknesses the building of dry-stone walls was successful, as demonstrated by the extent to which wall construction was undertaken, the period of occupation of the site and the present condition of many original walls.

Architectural features

Whilst there was little alteration to the construction techniques in the development of Great Zimbabwe, there were significant changes to the architectural features incorporated into the walls. The features introduced include returned steps, decoration, platforms and conical towers. The incorporation of some of these features is unlikely to have been possible without the improved regularity and coursing of the later wall styles. A discussion of these features is beyond the scope of this paper; they have been outlined elsewhere (Whitty, 1961).

Summary and conclusions

The form and appearance of any structure is intrinsically related to the materials used in its construction. Quarrying the naturally exfoliated steps by fire-setting produced parallel sided blocks ideal for dry-stone wall construction.

The unique nature of the wall construction found at Great Zimbabwe, and other madzimbabwe, shows that these dry-stone structures were an indigenous development. The form of construction that developed was intrinsically related to the materials available for wall building. The method of construction altered little during the development of the site.

The uniformity of coursing in later walling was mainly due to a change in the materials, rather than improvements in building technology. Poor bonding of the blocks and a high voids ratio in the core material are common to all wall styles at Great Zimbabwe.

The slenderness of wall construction generally increased during development of the site, reflecting an improved appreciation of dry-stone walling gained through

experience. However, inherent weaknesses in the internal structure of the walls showed little improvement and have generally been the overriding factor in the failure of the walls.

Finally, Great Zimbabwe represents the culmination of a tradition of dry-stone wall construction in Southern Africa. The walls remain an important testament to the ingenuity of the builders because of their size, complexity and the intuitive application of the materials available.

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